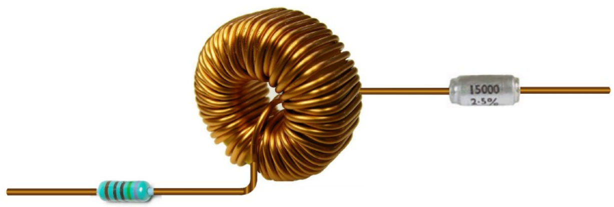
Brass Tacks

An in-depth look at a radio-related topic

Resistors

The three most fundamental passive electronic components are resistors, inductors, and capacitors. This basic discussion focuses on the ***resistor***, and explains the function and purposes of this simple but important device and how it's used in circuits. The hope is to give you a high-level understanding of it without drowning you in excessive detail.



One property shared by resistors, inductors, and capacitors is their ability to oppose current flow in a circuit. This flow opposition is not a decrease in *current speed*, but a ***decrease in current volume***, meaning number of charges being allowed to pass through it per second. A resistor opposes the flow of electrical current proportional to the voltage across it. With resistors, the opposition to current flow occurs because of ***resistance***, but with inductors and capacitors, the opposition to current flow occurs due to ***reactance***, which depends on the frequency of the current. In short,

- an inductor ***increases*** its opposition to current flow as the current's ***frequency increases***
- a capacitor ***decreases*** its opposition to current flow as the current's ***frequency increases***
- a resistor ***maintains*** its opposition to current flow, ***regardless of frequency***.

An interesting discussion also follows about what effect they have on circuits where they're used in multiples with each other or in combination with the other components. For now, let's explore the resistor, and save the discussion of the other two for another article.

Resistance

Resistor symbol

A resistor is a passive two-terminal electrical component that opposes current flow without regard to frequency, and is perhaps the most commonly used of all electronic components. Each discrete resistor possesses a pre-set amount of resistance (***measured in ohms***, symbol Ω) determined by its material composition, and whose nominal value is typically marked on the resistor itself by numerals or color bands. In spite of temperature and other environmental factors, the resistance value of each correctly functioning resistor does not vary outside its tolerance limits, often also marked on the resistor. As will be discussed, ***the primary purpose of a resistor is to drop voltage***.

Many of today's single resistors are made from finely powdered carbon mixed with powdered ceramic ("graphite paste"), held together by a resin. The ratio of the carbon to ceramic material determines the resistance value. Other resistor types include those made from metal oxide, metal film, and carbon film, each with advantages over the others.

If you examine water flowing in a creek, you'll notice right away that obstructions in the creek bed cause the water to reduce its flow downstream. If you want the flow to remain the same through the obstructions, you need to increase the volume of water before the obstructions. In

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an electrical circuit, the higher the resistance, the less current can flow through it for a given amount of voltage pressure. To force the same amount of current through a higher resistance, you must raise the voltage across (between the two sides of) the resistor to compensate. This results in a relationship known as Ohm's Law, which, in its simplest form, is

$$V = I \times R$$

or *the voltage across a resistor is equal to the current through it times its resistance value*.

As a side note, even though obstructions in the creek reduced the water flow, it did not change its speed, because speed is dependent on gravity, an outside influence, which is constant. What did change is the amount (volume) of water passing through the obstructions per second. By the same token, resistance doesn't reduce the speed of electrons in the circuit, but reduces the amount of electrons going through the resistor per second, because the speed is dependent on free-space permeability and permittivity, a pair of constant outside influences. This amount of electrons per second is measured in amperes (A).

Resistor combinations

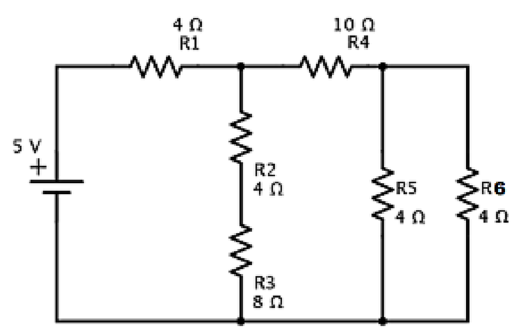
Sometimes it's handy or necessary to combine resistors to arrive at a desired value of resistance. For example, if your circuit needs a 40-ohm resistor, you might find that most stores don't stock resistors of that value. Instead, you can combine two resistors to arrive at the value you need. If you connect two resistors in **series**, *the values add up to the total*. If you connect them in **parallel**, the resulting value is less than either of the values, and in fact is their *product divided by their sum*.

For example, you can connect a 10-ohm resistor in series with a 30-ohm resistor, both of which are fairly common values, and they add up to the 40 ohms needed. If you wanted to place two resistors in parallel, you would need to find two values that satisfies this equation:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

It turns out that resistors of values $\mathbf{R_1}$ = 62 ohms and $\mathbf{R_2}$ = 110 ohms in parallel come very close to creating an $\mathbf{R_T}$ resistance of 40-ohms. (By the way, if $\mathbf{R_1}$ and $\mathbf{R_2}$ happen to be the same value, $\mathbf{R_T}$ is simply $\mathbf{R_1}$ ÷ 2, as used in the next example.)

In the circuit to the right, how much current is flowing out of the battery? First, combine the parallel resistances of $\mathbf{R_5}$ and $\mathbf{R_6}$, which is 4 Ω ÷ 2 = 2 Ω. That is now in series with $\mathbf{R_4}$, making 2 Ω + 10 Ω = 12 Ω. $\mathbf{R_2}$ and $\mathbf{R_3}$ are in series, so their total is 4 Ω + 8 Ω = 12 Ω, and that is in parallel with the previous 12 Ω from $\mathbf{R_4}$, $\mathbf{R_5}$, and $\mathbf{R_6}$, making the total so far 12 Ω ÷ 2 = 6 Ω. Finally, 6 Ω + 4 Ω from $\mathbf{R_1}$ makes 10 Ω total resistance of the entire network. From that, the current flowing out of the battery is 5 V ÷ 10 Ω = 0.5 A.



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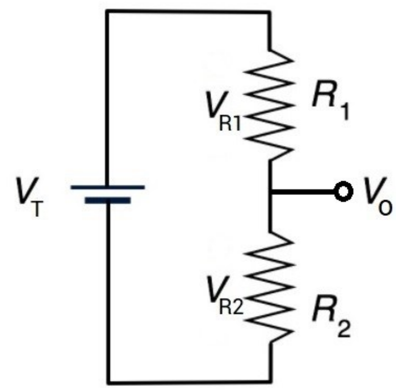
The voltage divider and KVL

Resistors can play a large role in converting a voltage value to one of a lesser value. Consider the circuit schematic to the right, with the resistors $\mathbf{R_1}$ and $\mathbf{R_2}$ in series, and the battery $\mathbf{V_T}$ across the series pair. To the battery, both resistors can appear as a single resistance ($\mathbf{R_1}$ + $\mathbf{R_2}$), and Ohm's Law provides that the total series current through both resistors is



$$I_T = \frac{V_T}{R_1 + R_2}$$

Since the same current $\mathbf{I_T}$ is flowing through both resistors, the voltage across only $\mathbf{R_2}$ is $\mathbf{I_T}$ x $\mathbf{R_2}$, or

$$V_{R2} = I_T \times R_2 = \frac{V_T}{R_1 + R_2} \times R_2$$

But this also means the voltage across only $\mathbf{R_1}$ is $\mathbf{I_T}$ x $\mathbf{R_1}$, or

$$V_{R1} = I_T \times R_1 = \frac{V_T}{R_1 + R_2} \times R_1$$

This circuit is known as a ***voltage divider***, because it divides the original battery voltage into two separate voltages, in our case $\mathbf{V_{R1}}$ and $\mathbf{V_{R2}}$.

An electrical principle known as KVL (Kirchhoff's Voltage Law) states that all voltages in a circuit loop in one direction add up to zero volts. In our example, that means both of the voltages across the resistor add up to the source voltage. To prove that, add up the two voltages.

$$\begin{aligned} V_{R1} + V_{R2} &= \frac{V_T}{R_1 + R_2} \times R_1 + \frac{V_T}{R_1 + R_2} \times R_2 \\ &= \frac{V_T R_1}{R_1 + R_2} + \frac{V_T R_2}{R_1 + R_2} = \frac{V_T R_1 + V_T R_2}{R_1 + R_2} = \frac{V_T (R_1 + R_2)}{R_1 + R_2} \\ &= V_T \end{aligned}$$

Since we know that $\mathbf{V_{R1}}$ + $\mathbf{V_{R2}}$ = $\mathbf{V_T}$, subtract $\mathbf{V_T}$ from both sides, we have $\mathbf{V_{R1}}$ + $\mathbf{V_{R2}}$ – $\mathbf{V_T}$ = 0 V, verifying KVL.

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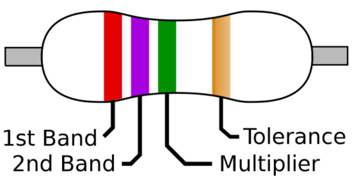
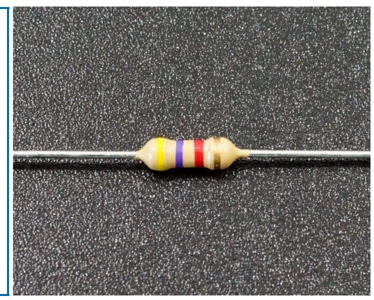
Color code

Discrete resistors (single components by themselves) are often marked with colored bands that indicate their nominal resistance values. The resistor color code provides a standardized way of reading and interpreting component values and properties, primarily for resistors, but also applies to some other component types as well. Essentially, it consists of three bands at minimum, two for the most significant digits, and one for the multiplier. The colors are defined as follows:



Black	0	Green	5
Brown	1	Blue	6
Red	2	Violet	7
Orange	3	Gray	8
Yellow	4	White	9



For example, a resistor with bands colored yellow-violet-red (on the right) has a value of 4 and 7, followed by 2 zeroes, making it a 4700-ohm, or 4.7 kΩ resistor. Many manufacturers will add a fourth band, which represents the resistor value tolerance, gold for 5%, silver for 10%, and none for 20%. So, the resistor in this example measures 4.7 kΩ, ±5%.

Wattage

One of the most important considerations when calculating a resistor circuit is the wattage, or the amount of power it needs to dissipate as a result of the voltage it drops. Back in our voltage divider example, if $\mathbf{V_T}$ is 15 VDC, $\mathbf{R_1}$ is 10 Ω, and $\mathbf{R_2}$ is 20 Ω, then

$$I_T = \frac{V_T}{R_1 + R_2} = \frac{15\ V}{10\ \Omega + 20\ \Omega} = 0.5\ A$$

The power dissipated by each resistor is defined by **P = I x V = I x I x R =** $\mathbf{I^2R}$; therefore,

$$P = I^2R = (0.5\ A)^2 \times (10\ \Omega) = 2.5\ W \text{ and } (0.5\ A)^2 \times (20\ \Omega) = 5\ W$$

If $\mathbf{R_1}$ is rated at less than 2.5 watts or $\mathbf{R_2}$ is rated at less than 5 watts, your under-rated resistor could burn up in this circuit. In fact, it's often good engineering practice to use resistors that have a wattage rating of twice the maximum calculated power demand.

Combining a couple of principles, if you don't have a (2.5 W x 2 =) 5-watt, 10 Ωresistor handy, you can use two 2.5-watt 20 Ω resistors in parallel. This will allow half the current to flow in each resistor, reducing the power dissipation of each resistor by half.

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Variable resistor

Just as there are resistors that have fixed values, there are also resistors that can be adjusted within a range of resistances. Perhaps the most common type of variable resistor is called a *potentiometer*, and many of these are variable by means of a rotating contact controlled by a knob, like in an audio volume control. Some are slide-operated, like a light dimmer or graphic equalizer control.

Each presents a constant resistance between the terminals spaced farthest apart, while the middle terminal allows for the variable resistance between it and either of the end terminals.

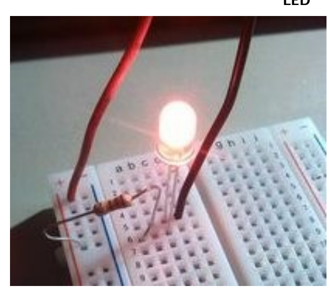
Other resistor applications

Resistors have uses beyond what has been discussed. Here are a few more examples of applications, in which resistors play important roles:

- **LED current control**

An LED (light-emitting diode) is indeed a diode, meaning that, when installed in forward-bias (so that current can flow through it) direction, it behaves almost like a short circuit. To limit the current through an LED, you should always connect a resistor between the diode and the supply voltage, and calculating the current-limiting (sometimes called *ballast*) resistor is easy.

Like most diodes, an LED exhibits a voltage drop, known as the *forward voltage*, and that must be taken into account when calculating the current-limiting resistor value. The difference between the supply (**V_S**) and LED forward voltage (**V_{LED}**), divided by the LED rated current (**I_{LED}**) will give you the ideal resistor value. For example, if the diode is listed at 3.0 V forward voltage with a 20 mA operating current, and you need to use it in a 12-volt circuit, then your ideal resistor value will be



$$R = \frac{V_S - V_{LED}}{I_{LED}} = \frac{12\ V - 3.0\ V}{20\ mA} = 450\ \Omega$$

- **Wrist strap**

Many technicians and hobbyists are aware of the damage that ESD (electrostatic discharge) from their bodies can inflict on sensitive electronics. To drain this static buildup, the worker will often wear a *wrist strap*, which electrically connects his/her body to ground by means of a resistor large enough to permit the static to drain gradually, often around 1 MΩ (1 meg-ohms, or one million ohms.)

The other end of the wrist strap is connected to an anti-static mat or directly to a ground of some sort, such as the ground pin of a three-prong outlet or an installed workbench ground.

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- **Time constant**

The current through an inductor cannot change instantly, and the voltage across a capacitor cannot change instantly. The rise and fall times of either of these quantities can be controlled by a resistor, which, together with the component's property (inductance or capacitance), establishes what's known as its time constant. The time constant is the amount of time a signal (voltage or current) drops from a steady level to $\mathbf{1/e}$ (about 36.8%) of the starting amount, or rises from a steady level to $\mathbf{1 - 1/e}$ (about 63.2%) of the starting amount, the letter e being Euler's number (the base of natural logarithms), about 2.7183.

One time constant (often denoted by the Greek letter τ) is defined as **RC** or **L/R**, depending on whether the component accompanying the resistor is a capacitor or an inductor, respectively, and is measured in seconds. Thus, if a 500 μF capacitor has a steady voltage of 10 V across it, and it's accompanied by a 470 Ω resistor, then the capacitor's voltage will drop to 36.8% of 10 V (10 V x 0.368 = 3.68 V) in

τ = **RC** = 470 Ω x 500 μF = 0.235 seconds.

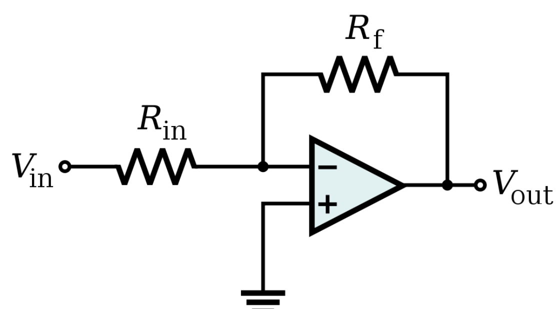
One important effect of the time constant is the determination of a filter's bandwidth, if the filter is constructed from inductors and/or capacitors. The calculation is

$$f_{3dB} = \frac{1}{2\pi\tau}$$

for each point on the frequency domain where the filter output signal is one-half the power level of that on the input, because –3 dB represents a half-power drop. Then, the filter bandwidth is the difference between two of those points.

- **Op-amp amplification control**

An op-amp (operational amplifier) is a compact circuit of complex analog micro-electronics that can perform a variety of functions, including that of an oscillator, active filter, detector, voltage follower, comparator, and yes, amplifier. If an op-amp is wired with a resistor ($\boldsymbol{R_f}$ for feedback resistor) connecting the output to the negative input, it functions as an amplifier. In fact, in the diagram to the right, the output voltage ($\mathbf{V_{out}}$) is related to the input voltage ($\mathbf{V_{in}}$) by – $\mathbf{R_f/R_{in}}$, known as its *gain*:



$$V_{out} = -V_{in}\frac{R_f}{R_{in}}$$

Summary

The ubiquitous resistor is perhaps the most common of all electronic components. It can be used to divide voltages, limit current, and control the rise-and-fall times of a passive filter component and the gain of an operational amplifier. Ohm's Law is useful for calculating resistor values in circuits, including the power dissipation.

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